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The Challenges of C-Band Missile Telemetry

Michael Rice

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THE CHALLENGES OF C-BAND MISSILE TELEMETRY

Michael Rice
Brigham Young University
Provo, Utah, USA

ABSTRACT

The differences between S-band and C-band systems are summarized in the context of missile telemetry. The most important challenges of C-band operation are identified: for air-to-air and air-to-surface systems, the relative small size of these missiles limits their ability to source additional DC power and handle increased heat loading due to potentially less-efficient C-band telemetry transmitters. For surface-to-air systems, the prospect of reduced link margin and potential tracking problems associated with narrower beamwidth antennas are the dominant issues for interceptor type systems whereas the power and heat issues associated with less-than-unity telemetry transmitters are the dominant issues for anti-air warfare systems. The potential problems for C-band telemetry of surface-to-surface systems appear to be more like the fixed-wing aircraft issues, many of which have been resolved.

INTRODUCTION

This is not an easy paper to write. Missile testing represents a bewildering array of different (and difficult) scenarios, many of which have little in common other than the presence of an airborne transmitter. Consequently, it is difficult for a single conference paper to capture all of the nuances of each and every system and nearly impossible to draw conclusions that apply fully to every missile test scenario. But we must try. This paper represents a first step in what the author hopes blossoms into a valuable technical dialogue.

The 2007 World Radio Conference (WRC) spectrum allocations to aeronautical telemetry were intended to reduce congestion in the traditional L- and S-bands. The hope was (and is) that by *augmenting* the spectrum available for testing, more meaningful tests (involving an increasing number of instrumented test articles each with an increasing telemetry data rate requirement) could be conducted with fewer scheduling delays. The post-WRC'07 frequency bands available to aeronautical telemetry are listed in Table 1. Note that lower C-band is available only for federal government users whereas middle C-band is available to both federal government and non-federal-government users. The NTIA and FCC have considered federal and non-federal use of lower C-band for aero-

Table 1: Aeronautical telemetry frequency bands after WRC'07

Name	Frequencies (MHz)	Comments
Lower L-Band	1435 – 1525	Telemetry is the primary service (part of mobile service) in the USA
Lower L-Band	1525 – 1535	Mobile satellite service (MSS) is the primary service, telemetry is secondary in the USA
Upper L-Band	1755 – 1850	
Lower S-Band	2200 – 2290	Telemetry (for unmanned vehicles only) is a co-primary service in the USA
Upper S-Band	2360 – 2395	Telemetry is the primary service in the USA[1]
Lower C-Band	4400 – 4940	WRC 2007 allocation to telemetry[2]
Middle C-Band	5091 – 5150	WRC 2007 allocation to telemetry[3]
Upper C-Band	5925 – 6700	WRC 2007 allocation to telemetry[4]

[1] Prior to 1997, the Upper S-band extended from 2310 to 2390 MHz. The lower portion of Upper S-band was reallocated in two separate auctions in 1997: 2320–2345 MHz was assigned to digital audio radio (today's Sirius-XM satellite radio) and 2305–2320 MHz and 2345–2360 MHz were assigned to wireless communication services.

[2] Prior to WRC 2007, lower C-band was available for aeronautical telemetry by federal government users in the USA. The WRC 2007 allocation extended use of this band for aeronautical telemetry to all of ITU Region 2. Non-federal-government users will not be allowed to use this band for time being, but may be in the future.

[3] In the USA, the NTIA and FCC made middle C-band available to aeronautical telemetry by both federal government and non-federal government users.

[4] The WRC 2007 allocation allows aeronautical telemetry on a non-interfering basis. Upper C-band is home to point-to-point microwave links by users such as railroads, oil companies, gas companies, etc. and VSAT satellite terminals used to link convenience stores, fast-food chains, etc.

nautical telemetry, but as of this writing, the NTIA and the FCC have agreed to pursue no regulatory action. Upper C-band is already crowded, but may be useable on a location-dependent basis. Those readers interested in the origins of the frequency band letter designations will find Table 2 interesting. The use of "C" for "compromise" to designate the 4–8 GHz band suggests the curious mental image of group of radio engineers arguing over the frequencies that define the S- and X-bands.

The potential for the WRC'07 allocations to alleviate the well-documented congestion at L- and S-bands has generated considerable interest in how telemetry systems might behave at C-band. The questions being asked are the usual ones: How is operation at C-band the same as L/S-band operation? How is it different and what changes need to be made to expand range capability to C-band? What is the impact of C-band on airborne instrumentation? On ground stations?

Recent tests at Edwards AFB described by Temple and Selbrede [2, 3] successfully demonstrated C-band telemetry operation for fixed-wing aircraft. As a result of these tests, the Test Pilot School (TPS) has expanded its telemetry capability to include C-band [4]. Given the current L-band congestion at the Air Force Flight Test Center (AFFTC), the expectation is that most of the TPS missions will use C-band telemetry in the foreseeable future.

Table 2: Origins of the frequency band designations (from [1])

Band	Frequency Range	Origin of Name
HF Band	3 – 30 MHz	**H**igh **F**requency
VHF Band	30 – 300 MHz	**V**ery **H**igh **F**requency
UHF Band	300 – 1000 MHz	**U**ltra **H**igh **F**requency
L Band	1 – 2 GHz	**L**ong Wave
S Band	2 – 4 GHz	**S**hort Wave
C Band	4 – 8 GHz	**C**ompromise between S and X
X Band	8 – 12 GHz	X for "cross" (as in crosshair) with reference to its use in WW II for fire control
Ku Band	12 – 18 GHz	**K**urz-**u**nder
K Band	18 – 27 GHz	**K**urz (German for short)
Ka Band	27 – 40 GHz	**K**urz-**a**bove
V Band	40 – 75 GHz	**V**ery High Frequency[5]
W Band	75 – 110 GHz	W follows V in the alphabet
mm Band	110 – 300 GHz	the wavelength is 1 – 3 mm

[5] This occurrence of the phrase "very high frequency" should not be confused with the use of the same phrase for the VHF band.

While the Temple-Selbrede tests answered the questions for fixed-wing systems, the answers for missile telemetry remain unclear. The fact that "missile telemetry" is such a diverse undertaking means general conclusions are nearly impossible to make. To help bring order to the chaos, the following approach is taken:

1. To manage the presence of so many variables, the discussion assumes the minimum number of simultaneous changes to the telemetry system. If a reader's current S-band system tests 16-inch diameter missiles, then a 16-inch diameter missile is assumed for the C-band discussion. The same is true for a 2.75-inch diameter system. If a reader's current ground station antenna uses a 5-meter parabolic reflector as the S-band receive antenna, then the same antenna, with the minimum retrofitting required for C-band operation, is assumed. This approach allows the reader to understand how C-band operation might impact each element of the telemetry system.

2. Missile systems are partitioned into three broad categories: Air-to-air and air-to-surface systems, surface-to-air systems, and surface-to-surface systems.

The challenges of C-band telemetry are different in each category and are discussed in detail later. Before that discussion, some general comments are in order.

SOME GENERAL COMMENTS

Modulations: PCM/FM and SOQPSK-TG PCM/FM is the dominant modulation used in S-band missile telemetry. The major factor for the dominance of PCM/FM over SOQPSK-TG for S-band telemetry is chronological: missile systems tend to last a long time and most of the current missile contracts were established prior to the adoption of SOQPSK-TG as an IRIG 106 standard in 2002. Consequently, highly integrated S-band telemetry packages based on PCM/FM were built-in to the contracts.

Because the bandwidth requirement for SOQPSK-TG is half that of PCM/FM, switching from S-band PCM/FM to S-band SOQPSK-TG essentially doubles the spectrum available for missile testing. Curiously, the prevailing thought in the missile telemetry community is that the logistical and contractual difficulties of such a change render it impractical. Because targets tend to be developed under less-stringent contractual constraints, SOQPSK-TG-based telemetry packages are increasingly common in drones and target missiles.

The issues that make C-band different from S-band are mostly independent of the modulation. It is through phase noise, frequency uncertainty, and Doppler shift that C-band operation has the potential to impact the performance of the modulation and demodulation. A commonly used rule of thumb is that oscillator phase noise increases 6 dB with each octave increase in the center frequency. Consequently, given the fact that C-band is just over one octave above S-band, one expects a 6-dB increase in oscillator phase noise. For bit rates of 5–10 Mbit/s and higher, such an increase is barely noticeable. At low bit rates (say, 100–200 kbits/s) such an increase in phase noise is a problem. Transmitters mounted in missiles experience a high degree of shock and vibration. Shock and vibration cause incidental FM and incidental FM contributes an additional source of phase noise. How significant this additional phase noise is depends on a number of very complicated factors. In the absence of any more detail, the only reliable generalization is that relative to S-band, the phase noise due to shock and vibration at C-band *won't be better*.

The Doppler shift is due to motion by the transmitter, the receiver, or both. The relative velocity between the transmitter and receiver may be resolved into two components: the tangential velocity v_t which is the velocity component perpendicular to the line-of-sight, and the radial velocity v_r which is the velocity component along the line of sight. The shift in carrier frequency is a function of the radial velocity component:

$$\Delta f = \frac{v_r}{\lambda} \quad \text{(cycles/s)} \tag{1}$$

where λ is the wavelength of the RF carrier. This shows that the Doppler shift increases with decreasing wavelength. Because C-band wavelength about one-half that of S-band, the Doppler shift at C-band is twice that at S-band. Consequently, receivers and demodulators need to accommodate higher frequency offsets. Whether or not this necessitates a change to existing receivers and demodulators (in addition to the changes required to channelize C-band) depends on the sensitivity of the S-band design to an uncompensated frequency shift as well as on the radial velocity component. The experience to date shows that SOQPSK-TG works just fine at C-band for fixed-wing aircraft. [2, 3].

Multipath Propagation Multipath propagation tends to be a problem in two scenarios in missile telemetry. The first is when the missile is low on the horizon from the receiver's point of view. Here strong "bounces" off the ground or ocean are the primary issue. The second scenario occurs at launch. In some cases, this is identical to the first scenario. For surface-to-air systems using large missiles, the launch complex often has towers and other structures that generate an additional source of multipath propagation.

Because C-band carriers have a shorter wavelength than S-band carriers, potential reflecting surface appear more "rough." The increased roughness tends to scatter more of the electromagnetic wavefront away from the receiver. This reduces the strength of the multipath interference. Another important factor in multipath interference is the beamwidth of the receive antenna. Because the receive antenna beamwidth is narrower at C-band than at S-band, the C-band antenna tends to attenuate off-boresite reflections more than S-band. Consequently, the increased "spatial filtering" at C-band tends to reduce the power of multipath propagation received by the demodulator.

In summary, C-band multipath propagation *is not worse* than S-band multipath propagation. A consequence of this observations is that existing solutions to multipath problems (such as the use of multiple ground-based antennas with best source selectors or strategically located receive antennas near the bases of launch complexes) should also work at C-band.

Antennas The gain of an antenna is a function of the ratio of the aperture size to the wavelength. Consequently, for a fixed aperture size, antenna gain *increases* with decreasing wavelength. But the increased gain is accompanied by increased directionality (i.e., narrower beams in the radiation pattern [transmit antennas] or the gain pattern [receive antennas]). This is the typical approach to receive antenna design. On the other hand, if the aperture size decreases as wavelength decreases in such as way that the ratio of aperture dimension to wavelength remains constant, then the gain remains the same. This is the typical approach to transmit antenna design.

In missile telemetry, the most common transmit antenna configuration is a wrap-around antenna. Wrap-around antennas comprise patches, whose optimal dimensions are determined by the wavelength. The telemetry signal is connected to each antenna element (patch) to approximate as closely as possible a uniform radiation pattern. The number of patches is determined by both the wavelength and the missile diameter. Consequently, multiband antennas using this configuration are hard. For a missile equipped with an S-band wrap-around antenna to operate in C-band, the S-band wrap-around antenna should be replaced by a C-band wrap-around antenna.

Suppose, for the purposes of illustration, that the S-band wrap around antenna comprises three patches as shown in Figure 1 (a) and suppose that the resulting radiation pattern is the one shown below the wrap-around antenna. The radiation pattern shows three lobes and three nulls. The nulls are a result of the interference pattern between adjacent patches. Because the radiation pattern is not uniform, antenna specifications in missile telemetry tend to a sort of "worst case" metric. An example might be "90% of the gain values must be greater than -7 dBi." Now consider the C-band wrap-around antenna shown in Figure 1 (b). Because the wavelength at C-band [6 cm (2.36 in) at 5000 MHz] is approximately half the S-band wavelength [13 ⅓ cm (5.25 in) at 2250 MHz], the dimensions of the C-band patches are about half those of the S-band patches and there are twice

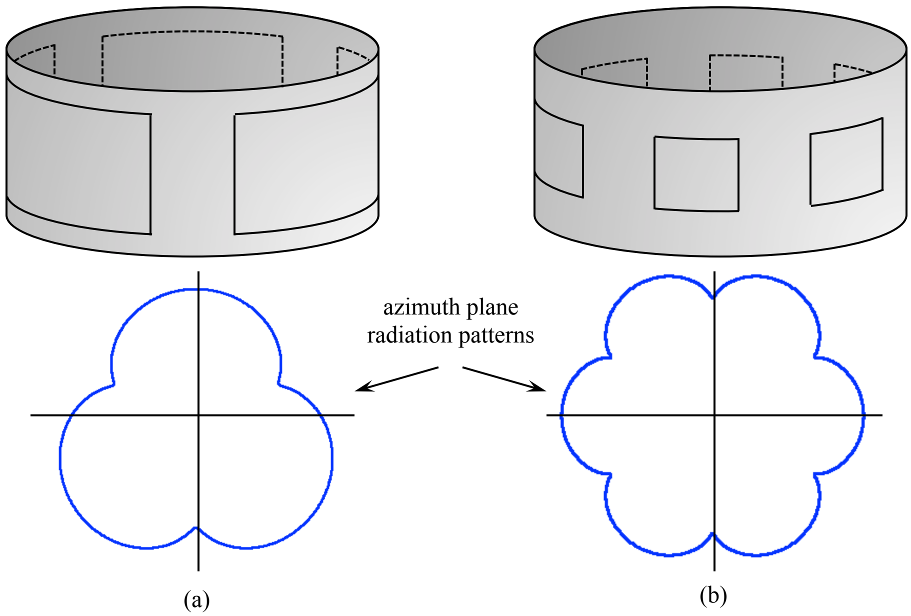

Figure 1: Wrap around antennas and corresponding azimuth plane gain patterns: (a) S-band; (b) C-band. The gain patterns are meant to illustrate the basic concepts and should not be interpreted as representations of real gain patterns.

as many patches in the C-band antenna. Consequently, the resulting radiation pattern displays six lobes and six nulls. Because the C-band antenna contains twice as many elements as the S-band antenna, the interference patterns tend to get more complicated and can be harder to control. As a result, it might be more difficult for a C-band wrap-around antenna to meet a "90% of the gain values must be greater than -7 dBi" specification.

The most common receive antenna configuration is the parabolic reflector. The boresite gain is

$$G_0 = \left(\frac{\pi D}{\lambda}\right)^2 \eta_i \tag{2}$$

where D is the diameter, λ is the wavelength, and η_i is the illumination efficiency. This shows that for a fixed diameter, the receive antenna gain increases with decreasing wavelength (increasing RF frequency). The beamwidth is proportional to λ/D and thus decreases with decreasing wavelength. The reduced beam width can have important implications for target acquisition and tracking.

Link Budgets The link budget does not capture all of the issues involved in the behavior of C-band telemetry, but it is a good starting point. A simplified version of the link budget equation is

[5]

$$\left[\frac{C}{N_0}\right]_{\text{dB}} = \underbrace{\left[P_T G_T(\theta,\phi)\right]_{\text{dB}}}_{\text{EIRP}} + \underbrace{\left[\left(\frac{\lambda}{2\pi R}\right)^2\right]_{\text{dB}}}_{\text{spreading loss}} + \left[\frac{G_R(\theta',\phi')}{T_{\text{eq}}}\right]_{\text{dB}} - [k]_{\text{dB}} - [L]_{\text{dB}} \quad (3)$$

where

P_T	=	transmitter power
$G_T(\theta,\phi)$	=	the transmit radiation pattern in the direction θ, ϕ
λ	=	the wavelength of the RF carrier
R	=	the distance between the transmitter and receiver
$G_R(\theta',\phi')$	=	the receive antenna gain in the direction θ', ϕ'
T_{eq}	=	the equivalent noise temperature of the antenna-receiver-demodulator system
k	=	Boltzman's constant (-228.6 dB-W/K)
L	=	all other losses, such as cable loss from the transmitter to the transmit antenna, polarization loss, tracking loss, atmospheric loss, rain loss, plume attenuation, etc.
C/N_0	=	the received carrier-to-noise density ratio[6]

All of the terms on the right-hand side of (3), except Boltzman's constant k, are wavelength-dependent, though some have a stronger dependence than others. A summary of these dependencies is as follows.

1. The terms $G_T(\theta,\phi)$ and $G_R(\theta',\phi')$ are the gains of the transmit and receive antennas, respectively. The dependencies between antenna gains and wavelength are summarized above.

2. The RF transmitter power P_T: As of this writing, the available C-band telemetry transmitters are capable of producing the RF power typical of missile telemetry (e.g., 1, 2, 5, and 10 W). It is also the case that the power efficiency of these transmitters is less than that of their L- and S-band counterparts. In terms of the parameters captured by the link budget, the term P_T in (3) is not a function of wavelength. The impact of power efficiency on system performance is described below.

3. The spreading loss is proportional to the square of the wavelength. Note that antenna gain is also proportional to the square of the wavelength.

[6]For FM systems, the quantity of interest is the "carrier-to-noise ratio" denoted C/N here. The relationship between C/N and C/N_0 in a bandwidth B Hz is

$$\left[\frac{C}{N}\right]_{\text{dB}} = \left[\frac{C}{N_0}\right]_{\text{dB}} - \left[B\right]_{\text{dB}}.$$

For digital communications, the quantity of interest is E_b/N_0. The relationship between E_b/N_0 and C/N_0 for a bit rate R_b bits/s is

$$\left[\frac{E_b}{N_0}\right]_{\text{dB}} = \left[\frac{C}{N_0}\right]_{\text{dB}} - \left[R_b\right]_{\text{dB}}.$$

4. The equivalent noise temperature T_{eq}: The dominant contributors to the equivalent system temperature are the "sky temperature" and the noise figure of the low-noise amplifier (LNA) at or near the antenna feed. The "sky temperature" does not show significant variation in the range of wavelengths corresponding to L-band through C-band. LNA noise figures are generally worse at C-band than at S-band; how much worse depends on the manufacturer, operating environment, etc. Consequently, one finds higher equivalent noise temperatures at C-band than at S-band.
5. The loss term L is, in general, higher at C-band than at S-band. Cable losses, atmospheric/rain attenuation, and plume attenuation are higher at C-band than at S-band. Furthermore, given the narrower beamwidth of an antenna operating at C-band, one can expect increased pointing error losses from the receive antenna.

The forgoing observations suggest the following conclusions:

1. Assuming the nulls in the wrap-around transmit antennas can be properly managed, the EIRP is independent of wavelength.
2. Theoretically, the increased spreading loss is offset by the increased G/T of the receiver system. But, because the T_{eq} is higher at C-band, G/T does not increase as much as the spreading loss. The net result is increased loss.
3. The additional losses are higher at C-band.

The main point is a C-band missile telemetry system must operate with less link margin than an S-band missile telemetry system. How much of a problem this is depends on the application.

AIR-TO-AIR AND AIR-TO-SURFACE SYSTEMS

Air-to-air and air-to-surface missiles tend to be small and fast-moving. Mission times are relatively short — from a few tens of seconds to two minutes. Whereas the distance flown by the missile after launch is relatively short, the sortie can often be far away from the telemetry receiving station — several tens to 100 miles. For this reason, airborne relays are often used in these test missions. For test sorties within the radio horizon of the ground-based antennas, test ranges tend to "run out of horizon" before they "run out of link budget."

Some missile systems are housed in canisters or inside the the aircraft fuselage prior to launch. Because propagation directly from these missiles to the ground-based telemetry antenna or airborne relay system is difficult, "re-radiation pods" are used to capture the telemetry signals from the missiles, demodulate the signals, then remodulate the bits on a different carrier using an unobstructed antenna. Typically 1/2-W, 1-W, 2-W, and 5-W transmitters are used to transmit telemetry signals carrying anywhere from several hundred kbits/s to 12 Mbits/s. As of this writing, most telemetry in this class takes place in S-band, the re-radiation pods use L-band as the downlink band, and instrumented targets tend to be in upper L-band.

The major challenges here are linked to the small missile diameter. Typically, a battery is used

Table 3: A summary of the DC current and heat dissipation requirements for S-band and C-band telemetry transmitters producing 5 W of RF output power. The current requirements are based on a 28 VDC power supply.

	S-Band $\eta = 29.5\%$	C-Band $\eta = 17.1\%$
I_{DC}	605 mA	1044 mA
P_{heat}	12 W	24 W

to supply power to the telemetry package in an air-to-air missile after launch. The DC-current available to power the telemetry transmitter is limited by the size and weight of the battery. The size and weight of the battery are limited by the size of the host system. Consequently, any change that requires more current may present a huge challenge.

The power required by a telemetry transmitter is determined by the RF output power P_{out} and the DC-to-RF efficiency of the telemetry transmitter η, defined by

$$\eta = \frac{\text{RF output power}}{\text{DC input power}} = \frac{P_{\text{out}}}{V_{\text{DC}} I_{\text{DC}}} \tag{4}$$

where V_{DC} and I_{DC} are the power supply voltage and current, respectively. The input power $V_{\text{DC}} I_{\text{DC}}$ is the power supplied by the missile power supply and is used to power all functions of the transmitter: the input circuitry, buffer amplifiers, clocks, signal processing hardware (either "analog" or "digital"), mixers, RF circuits, and RF power transistors. All of these contribute to a less-than-unity efficiency. Typically, the power supply voltage is fixed[1] so that the "power budget" is thought of in terms of current. The current required by a P_{out}-W telemetry transmitter with efficiency η operating with a V_{DC} power supply is

$$I_{\text{DC}} = \frac{P_{\text{out}}}{\eta V_{\text{DC}}}. \tag{5}$$

The largest single contributor is the RF power amplifier which consumes on the order of 50% of the input power. It is here that operation at C-band has the most impact.

A typical 5-W S-band transmitter has an efficiency of approximately $\eta = 29.5\%$. Assuming a 28 VDC power supply voltage, the required DC current is 605 mA. As of this writing, a typical value for the efficiency of a 5-W C-band transmitter is $\eta = 17.1\%$. As before, assuming a 28 VDC power supply voltage, the required DC current is 1044 mA. These data are summarized in Table 3. Because C-band transmitters are less efficient than their S-band counterparts, more current is required to produce the desired RF output power. This means that C-band operation requires either a larger battery or shorter transmission time.

[1] 28 VDC is a common value. However, use of the word "fixed" needs to be qualified in this context. The true value of a 28 VDC missile power supply may vary from 22 VDC to 34 VDC. Perhaps "nominal" is a better word than "fixed." Even so, power budgets are most often quantified in terms of current and this thinking presumes a "fixed" power supply voltage.

The other important issue raised by less-than-unity transmitter efficiency is heat dissipation. In large test articles, the test article can be used as the "heat sink." Unfortunately, the relatively small sizes of air-to-air systems makes using the missile body as the "heat sink" problematic. To first-order approximation, the heat load generated by the telemetry transmitter is

$$P_{\text{heat}} = V_{\text{DC}} I_{\text{DC}} - P_{\text{out}} = \left(\frac{1-\eta}{\eta} \right) P_{\text{out}}. \tag{6}$$

For a fixed output power, the heat load increases as the efficiency decreases. Examples for a 5-W transmitter are shown in Table 3. Here, the decreased efficiency associated with C-band operation produces an increased heat load.

SURFACE-TO-AIR SYSTEMS

This class of systems includes "interceptor missiles" (and their targets) and "anti-air warfare missiles" (and their targets). Because the issues for these two systems are different, they are considered separately.

Interceptor Missiles These missiles tend to be much larger than their air-to-air/air-to-surface counterparts. A typical test scenario involves the launch of one or more targets (large missiles) and one or more interceptor missiles. The "end game," where the interceptors and targets meet with hopefully devastating results, occurs at a high altitude. Safety considerations and the long distances over which the tests are conducted tend to push the locations of operational tests over the ocean. Both the interceptors and targets are instrumented, and telemetry downlinks primarily use the upper L- and S-bands. Telemetry data rates are high — several tens of Mbits/s and mission duration is a function of the target and interceptor trajectories. It is not uncommon for telemetry links to operate over several hundred to 2,000 miles.

Because of their large size, the issues of power supply and heat loading are less critical in this class. The test challenges are associated enormous distances over which the link must be maintained. Because of the large distances separating the airborne transmitter and ground-based receiver, telemetry receiving sites use large receive antennas whose correspondingly large gains are requited to close the link. Examples include 3-meter, 5-meter, and 7-meter dishes at Kwajalein Island, a 13-meter dish at PMRF, 44-foot and 35-foot dishes at Vandenberg AFB, 20-foot, 50-foot, and 80-foot dishes at Cape Canaveral.

Link margin is at a premium in these scenarios and the loss of even a few dB can be huge problem. As explained earlier in this paper, relative to S-band, C-band operation is characterized by increased atmospheric and rain attenuation, increased connector and cabling, reduced G/T, and possible reductions in transmit antenna gain. These characteristics all contribute to reduced link margins and comprise one of the major challenges with C-band.

An additional concern for link margin is the behavior of wrap-around antennas at C-band. This behavior was explored above in the discussion accompanying Figure 1. The fact that the radiation

Table 4: A comparison of beamwidth of a parabolic reflector antenna as a function of RF carrier frequency and antenna diameter. The carrier frequencies used to compute the beamwidths are 1780 MHz (Upper L-band), 2245 MHz (S-band), and 5000 MHz (C-band).

	UL-Band		S-Band		C-Band	
diameter (m)	$\phi_{\text{null-null}}$	$\phi_{\text{3dB-3dB}}$	$\phi_{\text{null-null}}$	$\phi_{\text{3dB-3dB}}$	$\phi_{\text{null-null}}$	$\phi_{\text{3dB-3dB}}$
3	7.860°	3.371°	6.230°	2.673°	2.796°	1.200°
5	4.714°	2.022°	3.737°	1.604°	1.678°	0.720°
7	3.366°	1.445°	2.669°	1.145°	1.198°	0.514°
10	2.356°	1.011°	1.868°	0.802°	0.839°	0.360°
13	1.813°	0.778°	1.437°	0.617°	0.645°	0.277°
15	1.571°	0.674°	1.245°	0.535°	0.559°	0.240°
17	1.386°	0.595°	1.099°	0.472°	0.493°	0.212°
20	1.178°	0.506°	0.934°	0.401°	0.419°	0.180°

patterns for C-band wrap-around antennas can have twice as many nulls as their S-band counterparts is a real concern. The "nightmare scenario" for these tests is the situation where, during the "end game" (say, the last second of the test), the airborne interceptor or target has rolled into a position such that the ground-based receive antenna is looking directly into one the nulls of the transmit radiation pattern.

The second major potential issue with C-band operation is receive antenna pointing. As explained above, the test scenarios for interceptor missiles require large ground-based receive antennas: parabolic reflector antennas with diameters ranging from a few meters to 20 meters. Large antennas provide the gain required to close the link, but achieve this gain with a narrow beamwidth. A beamwidth that is too narrow may negatively impact the ability to (re)acquire an airborne transmitter. The most difficult scenario in this class is where the missile (or target) "pops up" over the radio horizon. The narrower the receive antenna beamwidth, the more precisely the "pop up" position must be known—and this is difficult.

To give the reader a feel for the potential magnitude of the problem, a comparison of the beamwidth of a parabolic reflector antenna as a function of frequency band and antenna diameter is listed in Table 4. The data show that as frequency or diameter or both increase, the beamwidth decreases.

C-band experiments at the Air Force Flight Test Center [2] and the Test Pilot School [3] document satisfactory C-band tracking performance using an 8-foot (2.4 m) antenna. C-band channel sounding experiments, described in [6], also demonstrated satisfactory tracking behavior using the 8-foot receive antenna. The author's experience during these channel sounding experiments was that the antenna operators found it more difficult to acquire the C-band signal, but that post acquisition autotracking worked well. The data of Table 4 show that dishes with diameters 10-meters or more have smaller beamwidths than the current crop of L- and S-band antennas. In this sense, the C-band target acquisition with such dishes is unknown territory.

As for tracking, C-band performance may be inferred from the fact that C-band radars routinely

track missiles and other airborne targets using similarly-sized antennas. The temptation is to conclude that C-band tracking of telemetry signals will not be a problem when using large radar-sized dishes. The enthusiasm may not be warranted: C-band radars are equipped with special reinforced mounts and dedicated servo-motors specifically designed for the task. Because the assumed migration plan is to retrofit existing ground station antennas with C-band feeds, it is an open question, as of this writing, whether such retro-fitted telemetry antennas can be used to acquire and track a C-band telemetry signal.

Anti-Air Warfare Missiles A typical example of this class is a missile, launched from a ship, whose intended targets are fixed and rotary-wing aircraft, UAVs, or anti-ship cruise missiles [7]. The tests are usually conducted on a sea range with the telemetry receiver sites located on the shore or nearby island. Like their air-to-air or air-to-surface counterparts, these missiles tend to be small and travel at high velocities. Consequently, weight, heat, and available current are important considerations whose impacts have already been explored in the context of air-to-air and air-to-surface systems.

Additional concerns here are multipath interference and radio horizon. Multipath interference is not worse at C-band. Unlike the interceptor missile scenario, the “end game” tends to be at a much lower altitude. Thus the radio horizon tends to be on the order of one- to two-hundred miles. This limits the distance over which radio telemetry link must be closed. Because the usable radio horizon depends on the altitudes of the airborne transmitter and ground-based receiver, the choice between L-, S-, or C-band has very little (if any) impact on this issue.

SURFACE-TO-SURFACE SYSTEMS

Cruise missiles dominate this class. A cruise missile is characterized by an airframe with small wings and a tail assembly for stabilization. The missile is usually powered by a jet engine thus enabling a non-ballistic trajectory. The range is few hundred to one thousand miles [8].

In the context of this paper’s emphasis, cruise missiles testing is quite similar to fixed wing aircraft testing. The presence of a jet engine means available power is rarely the limiting factor. The relatively large size is able to accommodate the heat load of less-than-unity efficiency telemetry transmitters. The major difference between a cruise missile test and a traditional fixed-wing aircraft test is the distance over which the test must be conducted. For long range tests, a “chase aircraft” is used to relay or record the cruise missile telemetry signal.

Because a typical cruise missile test is very similar to a fixed-wing aircraft test, the lessons learned from the Temple-Selbrede tests [2, 3] are relevant. Based on this information, the tentative conclusion is that operation at C-band presents few challenges not already addressed by the fixed-wing aircraft test community.

CONCLUSIONS

In summary, the general differences between S-band and C-band propagation have been summarized in the context of missile telemetry. Of all the differences between C- and S-band systems, three issues have emerged as potentially significant challenges: 1) reduced power efficiency of C-band transmitters, 2) reduced link margin, and 3) narrower antenna beamwidths.

The first issue is most important for air-to-air and air-to-surface missiles. Because of their small size, these systems are limited in their ability to source power to the telemetry transmitter and handle the heat generated by less-than-unity efficiency telemetry transmitters. Because link margin has not been a limiting factor for air-to-air and air-to-surface missile testing at S-band, it is not anticipated that issues 2 and 3 will be significant challenges at C-band.

For "interceptor missile" surface-to-air systems, issue 1 is less important because the missiles tend to be larger and capable of handling higher heat loads and sourcing more power. The significant challenge is ultimately link margin. Link margin is already a major concern at S-band. The prospect of lower link margins associated with C-band operation is a real concern. Higher gain receive antennas may not be a feasible solution because higher gain dishes are necessarily larger diameter dishes, and larger diameter dishes have even narrower beamwidths. Too-narrow beamwidths could pose huge problems for large retro-fitted telemetry antennas. On the other hand, "anti-air warfare missile" surface-to-air systems are dominated by the same challenges as the air-to-air missiles.

Finally, surface-to-surface missiles tend to look like fixed-wing aircraft. The issues for C-band operation for fixed-wing aircraft were explored in [2, 3]. Consequently, C-band testing of surface-to-surface missiles presents few challenges not already addressed by the fixed-wing community.

Whether or not these issues are insurmountable depends on a number factors impossible to list here. One thing that can be counted on is the dedication of creative test engineers to make impossible things work. C-band operation is not the first time the test community has been faced with tremendous technical challenges, and it is almost certain this will not be the last time.

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